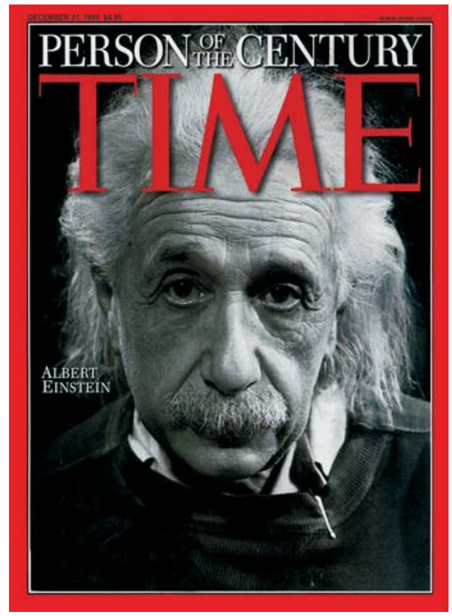
Chapter 2. Scientific Goals and Missions

Beyond Einstein: The Science

A century ago, Albert Einstein began creating his theory of relativity—the ideas we use to understand space, time, and gravity—and took some of the first steps towards the theory of quantum mechanics, the ideas we use to understand matter and energy. *Time* magazine named Einstein the "Person of the Century" because his ideas transformed civilization, but his work is not finished: spacetime is not yet reconciled with the quantum.



Einstein's general theory of relativity opened possibilities for the formation and structure of the Universe that seemed unbelievable even to Einstein himself but which have all been subsequently confirmed: that the whole Universe began in a hot, dense Big Bang from which all of space expanded; that dense matter could tie spacetime into tangled knots called black holes; that "empty" space might contain energy with repulsive gravity. Despite these discoveries, we still do not understand conditions at the beginning of the Universe, how space and time behave at the edge of a black hole, or why distant galaxies are accelerating away from us. These phenomena represent the most extreme interactions of matter and energy with space and time. They are the places to look for clues to the next fundamental revolution in understanding—Beyond Einstein.

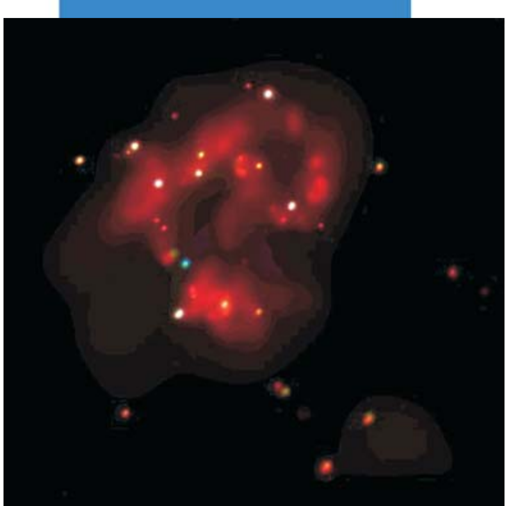
"The most beautiful thing we can experience is the mysterious. It is the source of all true art and science. Those to whom this emotion is a stranger, who can no longer pause to wonder and stand rapt in awe, are as good as dead: their eyes are closed."
—Albert Einstein

Edges of Spacetime and Black Hole Horizons

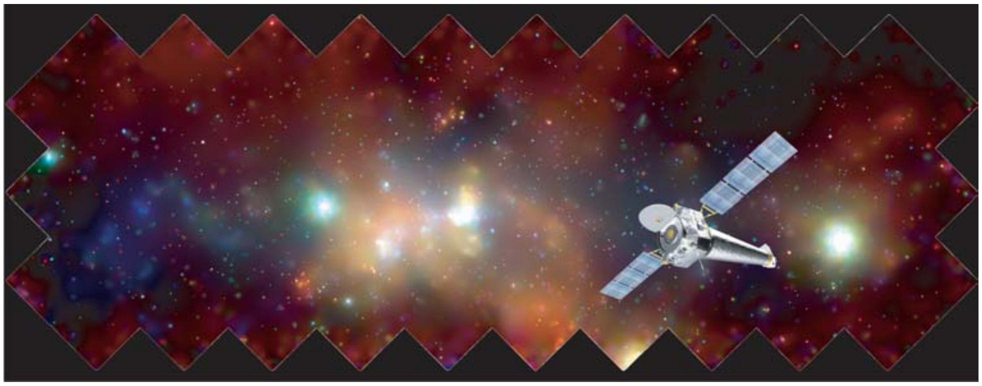
Most of what we know about gravity comes from experiments within the Solar System, where gravity is weak. These confirm Einstein's theory that gravity is the one universal force connecting all forms of mass and energy. It is universal because it is a property of space and time itself.

Einstein's general theory of relativity predicts that gravity should appear in its purest form in two ways: in vibrations of spacetime called gravitational waves, and in dense knots of curved spacetime called black holes. So far we have only circumstantial indications that these two astonishing predictions are true. *Beyond Einstein* missions will obtain *direct* evidence. Only data collected from these so-far invisible regimes can enable us to find out whether Einstein's theory is complete.

If it is, Einstein's theory tells us that a black hole is made of pure gravitational energy. It can have mass and spin but should contain no matter. Though we know the Universe contains many black holes, we have yet to see one in detail. The general theory of relativity provides a mathematical picture of what one should be like. At the heart is a singularity, where space and time are infinitely curved and



Chandra X-ray Observatory image of possible intermediate mass black holes accreting gas in the Antennae pair of colliding galaxies.



NASA's Chandra X-ray Observatory was launched in 1999. It is named after the Nobel Laureate Subrahmanyan Chandrasekhar, who developed the detailed mathematical theory of collapsed stars. Some of the Observatory's greatest discoveries include:

- Evidence for black holes of mass intermediate between those of stars and the supermassive black holes in galactic nuclei.
- Evidence that the X-ray background is produced by black holes so obscured by gas and dust as to be invisible to optical telescopes.
- Evidence for astonishingly bright clumps or rings of matter falling into black holes.
- Evidence that black holes in binary star systems are indeed bottomless holes as Einstein's theory predicts.

energy is infinitely concentrated. Around the singularity is a region from which nothing can escape. The edge of this region is called the event horizon. There, time is so warped that it seems, from outside, to have stopped.

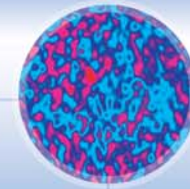
How could we find out if such objects really behave in this weird way? We could drop an astronaut near a black hole. As she fell in, Einstein predicts that the hands of her watch would appear to us to slow down and practically stop as she approached the event horizon. But she and her watch would fade from view so rapidly that we could never see her (or her watch) cross the event horizon. Yet to the falling astronaut, everything would seem normal as she crossed the event horizon. Unfortunately once across, nothing could save her. Tides would rip her to pieces near the central singularity.

Fortunately, there are more humane ways to find out if black holes are really as Einstein predicts. We can instead observe radiation from atoms of gas as they fall in. The frequency of their light is like the ticks of a clock. Changes in that frequency are caused by the motion of the gas—the familiar "Doppler effect" change in tone you hear as an ambulance races past—and by

"The black holes of nature are the most perfect macroscopic objects there are in the Universe: the only elements in their construction are our concepts of space and time."

—*Subrahmanyan Chandrasekhar*

[Nobel Prize, 1983]



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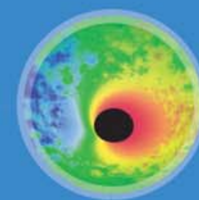
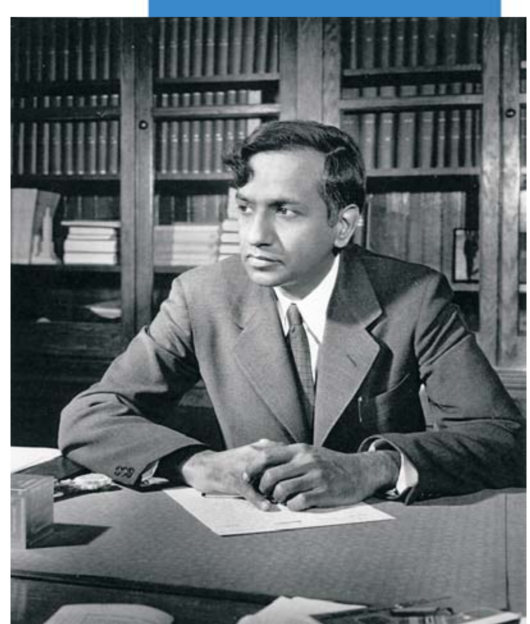


black holes

dark energy

"I was immediately hooked! You are stirring the imagination and interest of today's kids!" —Testimonial from user of Chandra education materials



Because $E = mc^2$, the energy of curved spacetime has mass. A black hole is a knot in spacetime so curved that the mass-energy of the curvature can keep the knot from unraveling. To describe everything about an isolated black hole, one needs only two numbers: its mass and its spin. Electric charge is shorted out. No other deviations from smooth perfection are possible: no mountains, no magnetic fields, no anything else. Physicists say that "black holes have no hair."

Because of this no-hair rule, the orbits of stars and other bodies around black holes are determined entirely by the mass and spin of the black hole. The orbiting bodies vibrate spacetime. The LISA mission will use these vibrations (gravitational waves) to track their orbits and show whether the black holes are really as "bald" as Einstein's theory predicts.

When we talk about observing the sky in radio waves or X-rays, we talk about "seeing" things, even though our eyes cannot see radio waves or X-rays. Similarly, we refer to "hearing" gravitational waves even though they are vibrations in the fabric of spacetime, not the vibrations of water or air that our ears hear.

the gravitational redshift due to spacetime curvature. Watching the spectra of these flows can thus reveal many details of the matter and its spacetime environment.

The light from these atoms can be very bright. Streams of matter falling into a black hole accelerate to nearly the speed of light; when they collide, they heat up and radiate enormous amounts of light. A car powered with a black hole engine would get a billion miles to the gallon. Mass-energy not radiated falls into the hole, adding to its mass and spin. The spin of the hole can give matter nearby a kick and, with the aid of magnetic fields, can even accelerate it into powerful jets of outflowing particles.

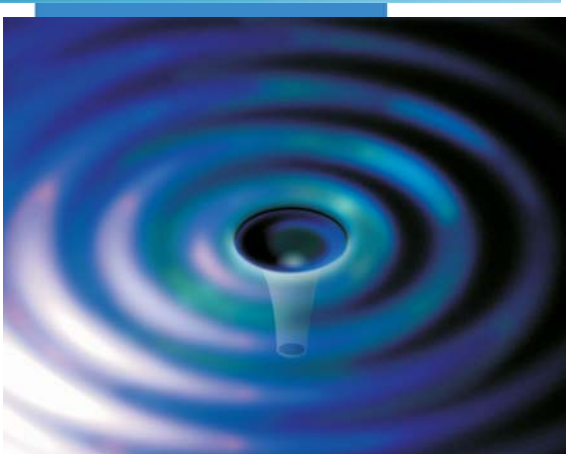
The *Beyond Einstein* program will systematically determine the fate of this matter. The Black Hole Finder Probe will survey the Universe seeking radiation from matter falling into black holes and mapping their locations; Constellation-X will study the spectra of atoms as they fall in; and in the distant future, the Black Hole Imager will create moving images of the swirling matter right down to the edge of the event horizon.

Cosmic Cacophony: Gravitational Waves

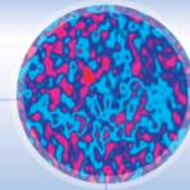
Black holes can also be studied by listening for the "sounds" they create, a novel form of energy called gravitational waves.

Since ancient times, astronomers have used one form of energy to study the Universe. Called simply "light," it includes X rays and radio waves and all the colors of the rainbow in between. Light is made of vibrating waves of electric and magnetic fields traveling through space.

In Einstein's theory of gravity, energy can also be carried by vibrating waves of space and time, which travel at the speed of light. In the same way that black holes are made just of space and time, gravitational waves are also "pure" space and time. They interact very weakly with matter and penetrate anything without losing strength. While this makes them powerful probes of extreme conditions, it also makes them hard to detect. They interact so weakly with measuring apparatus that only in the past few years



The Sun and planets of the Solar System very slightly bend space and time, causing them to fall around each other, and satellites to fall around the Earth. A black hole bends space and time so tremendously that time stops at its horizon's edge and neither matter nor energy can escape from within the horizon.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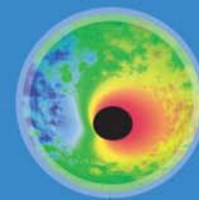

black holes


dark energy

has technology advanced to the point that we are confident we can build equipment to detect them.

The most powerful outflows of energy in the Universe are not carried by light but by gravitational waves emitted when two black holes orbit, collide, and merge. In the final minutes or hours before the merging of a single pair of supermassive black holes, a gravitational power of about 10^{52} watts is radiated. This is a million times more power than all the light from all the stars in all the galaxies in the visible Universe put together, and millions of times more powerful than the most powerful single sources of light: gamma-ray bursts. It is possible that the Universe contains more of this gravitational radiation than it does light.

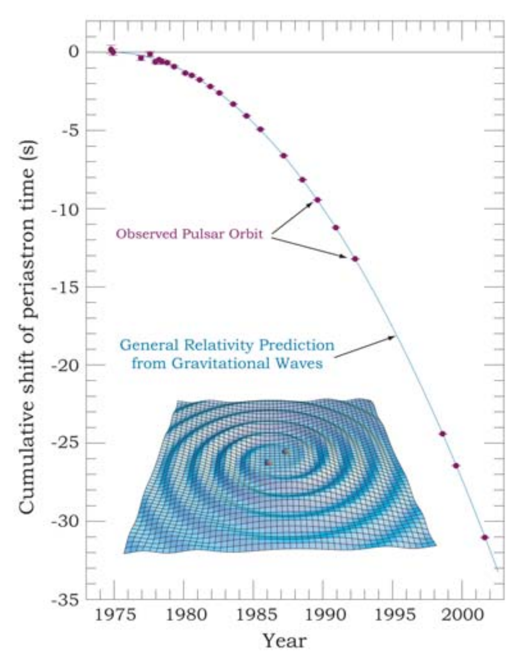
Detecting gravitational waves will give Einstein's theory a workout it has never had before. We know that it works pretty well in normal circumstances—without spacetime curvature technology in their software, airplanes using GPS navigation would miss their runways by miles—but gravitational waves offer much more profound potential. They will let us listen carefully to the most violent events in the Universe, the collision and mergers of black holes. What goes on there is a swirling knot of spacetime interacting mostly with itself. A black hole merger can also briefly expose to observation the singularity at the heart of the black hole, where Einstein's theory must fail. The sounds of the Universe will tell us how well Einstein's ideas still work in these extreme conditions. They will also allow us to penetrate times and places impossible to see with ordinary light, such as the birth of our Universe. They might reveal startlingly violent events, such as the formation of our three-dimensional space from an original space with more dimensions.

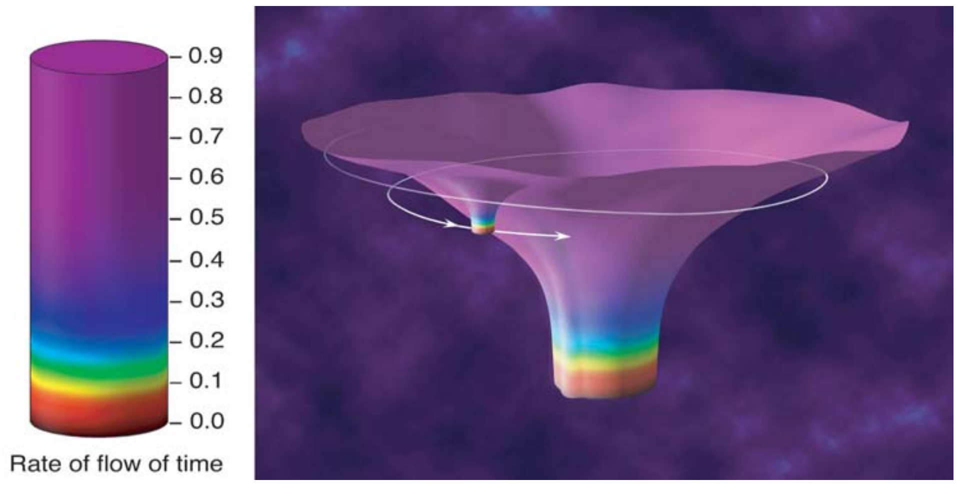
Gravitational waves produce tiny jiggles between masses that are floating freely in space, isolated from all forces other than gravity. The distances between the masses can be monitored using laser interferometry. An early generation of such systems has now been deployed on the ground—the NSF-funded Laser Interferometer Gravity-wave Observatory (LIGO) in the US and similar systems worldwide. It is hoped that these systems will make the first detection of gravitational waves from some sources of high-frequency waves. The *Beyond Einstein* Great Observatory LISA will operate in a broad band at much lower frequency. It will detect entirely different sources in great numbers and with exquisite precision.

In 1967, the first radio pulsar was discovered by Jocelyn Bell and Anthony Hewish (for which Hewish received the Nobel Prize in 1974). Pulsars were quickly identified as neutron stars, the incredibly compressed remnants of the supernova explosion of stars.

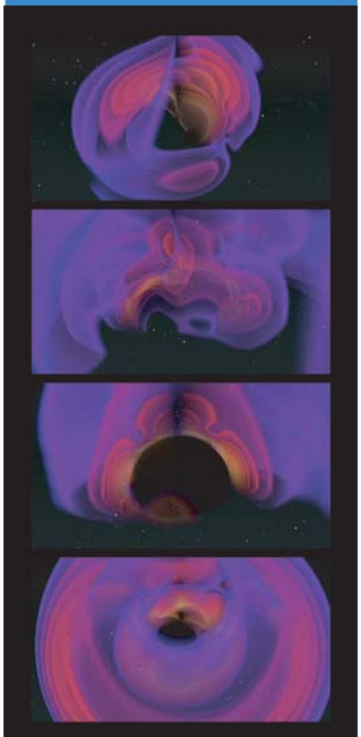
In 1974, Russell Hulse and Joseph Taylor discovered the first binary pulsar PSR 1913+16: one of two neutron stars orbiting each other every 8 hours. The general theory of relativity predicts that as the stars orbit each other, they stir spacetime around them and radiate gravitational waves, causing them to spiral together.

In 1993, Taylor and Hulse received the Nobel prize for showing that since 1974 the neutron stars have been spiralling towards each other at exactly the rate Einstein's theory predicts, due to gravitational waves. The gravitational waves from binary stars like this await direct detection by LISA and LIGO.





The warping of spacetime by a small black hole spiraling into a large one. LISA will measure this warping very precisely: the slowing of time (coded in color), the twisting of spacetime by rotation, and the size of the tide raised by the small black hole.



Supercomputer calculation of the gravitational waves produced in the merger of two supermassive black holes (Courtesy E. Seidel and W. Benger)

The most powerful gravitational waves come from quickly-changing systems with very strong gravity, so LISA's strongest signals will probably be tones from black holes spiraling into other supermassive black holes. LISA will also detect for the first time gravitational waves from calibrator sources (such as orbiting pairs of white dwarf stars) that have been studied by optical telescopes.

LISA will break ground for the new science of gravitational wave astronomy. The vision mission Big Bang Observer will extend the reach of gravitational wave astronomy towards its ultimate limit—detecting the quantum noise from the inflationary Universe.

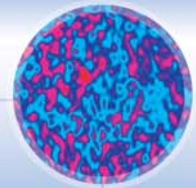
The Beginning of Time

The Universe is expanding, and abundant evidence now shows that it began in a hot, dense state—the Big Bang. The general theory of relativity explains how the expanding Universe works, but on its own it does not explain what made the Big Bang happen in the first place.

Clues have been found in the relic heat from the Big Bang, the Cosmic Microwave Background (CMB). Light that has been traveling to us since the Universe was 300,000 years old. Observations reveal minute temperature fluctuations in the brightness of the CMB that show that the matter content of our Universe, while remarkably smooth when the relic heat began its journey to us, had already been imprinted with perturbations at a much earlier time. These have now grown into the galaxies of stars illuminating our sky. We are therefore faced with a conundrum: Why has matter in the Universe *clumped* into galaxies and clusters of galaxies spread *smoothly* throughout space?

"Inflationary cosmology" provides one explanation of why the Universe is very smooth, yet not perfectly so. A still-mysterious form of energy generated a repulsive force that caused the early Universe to expand at a fantastic rate. This expansion stretched and smoothed any existing inhomogeneities in spacetime.

But the inflation field, like all energy fields, was subject to quantum fluctuations. These led to imperfections in the cosmic expansion—the Big Bang got a slightly bigger kick in some places than in others. The effect of a single quantum fluctuation was enor-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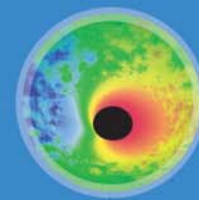

black holes


dark energy

In 1978 Arno Penzias and Robert Wilson received the Nobel prize for their 1965 discovery of the cosmic microwave background (CMB), which showed that our Universe began with a hot and nearly uniform Big Bang. This microwave radiation has been propagating towards us since the atoms in the Universe formed, when the Universe was 300,000 years old.

Arno Penzias and Robert Wilson and the historic Bell Labs horn antenna, discoverers of the relic Cosmic Microwave Background of the Big Bang.

Within a few years of this discovery, theoretical astrophysicists around the world predicted that because the Universe today is not uniform, the CMB should not look precisely uniform either. It should show seeds of the irregularities which would later turn into clustering galaxies. In 1989, NASA launched the Cosmic Background Explorer (COBE), and it discovered these predicted nonuniformities.

In 2000, an NSF/NASA balloon flight, BOOMERanG, for the first time mapped the details of the microwave background fluctuations in a small region of the sky.

The Wilkinson Microwave Anisotropy Probe (WMAP), a NASA mission launched in June 2001, is making measurements of these small-scale nonuniformities over the entire sky. The resulting map will reveal the geometry of the Universe and the nature of primordial perturbations. WMAP will also help determine the baryon density, Hubble parameter, dark matter density, and dark energy density, all indicators of the contents of the Universe.

mously inflated along with the Universe itself. Sky maps of the CMB show a pattern of fluctuations very much like that predicted by inflation.

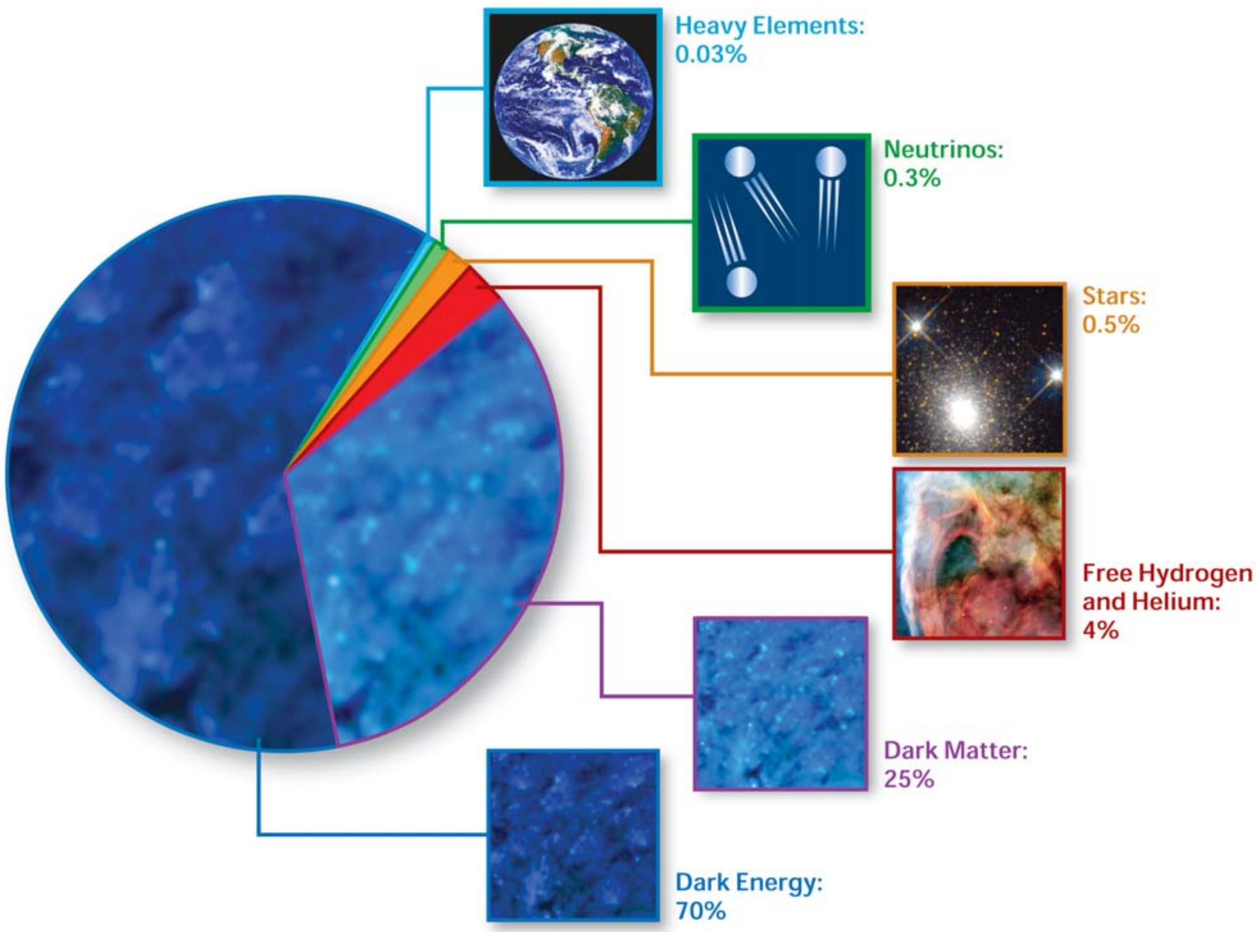
Nevertheless, we are far from certain that the inflationary scenario is correct. Even if inflation is the right story, the details of the process remain a mystery. We need new data to help decide whether the early Universe underwent a period of rapid inflation, and if so, what was the mechanism responsible for driving it.

We now understand a way to uncover these secrets. Calculations predict that in addition to its energy field fluctuations, inflation should have created single “particles of spacetime” called gravitons. The gravitational waves of longest wavelength (with periods of three billion years!) should have left a subtle pattern in the polarization of the light of the CMB.

The “Inflation Probe” will seek this subtle pattern. The strength and details of the pattern will tell us about the properties of the mysterious inflation field that powered the Big Bang.

“I am so thankful that I just saw on TV the Runaway Universe today and then discovered this website tonight. How can we be so lucky as to have these educational tools available? While I am a great-grandmother of two and have not studied chemistry, math or physics ever, I am hooked. Please keep giving this inspiring information to us and especially to the young future scientists.”
—Betty H., NC.

COMPOSITION OF THE COSMOS



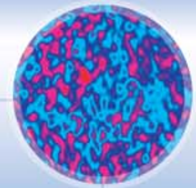
When first broadcast, NOVA's television show Runaway Universe *on dark energy was watched by 2.1 million Americans—almost as many as viewed all cable news network stations combined.*

Dark Energy and the Accelerating Universe

Deep as Einstein's general theory of relativity may be, it remains silent on a profound question: Is empty space really empty? Inflation models predict that it was not so in the past, and it may not be so today either. Einstein introduced a "cosmological constant" into his equations to represent the possibility that even empty space has energy and couples to gravity. The unknown magnitude of the cosmological constant is set by parts of physics beyond Einstein's understanding—and, at present, our own.

The new discovery that the expansion of the Universe appears to be accelerating suggests the presence of something dubbed "dark energy" that drives space apart. It seems likely that we have roughly measured the value of a cosmological constant or something like it.

This new discovery is already widely accepted because it explains many observations. The first indication was that the rate of expansion of the Universe has been increasing, revealed by Type Ia supernovae. Supporting evidence comes from studies of global geometry, structure formation, cosmic age, and galaxy clustering. They leave little doubt that in some sense Einstein's "cosmological constant" is a reality. The energy of the Universe is dominated by empty space whose gravitational effect is to pull the Universe apart.



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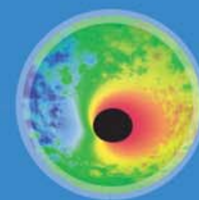
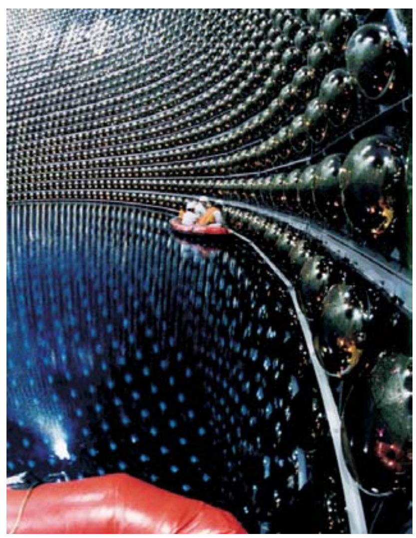


black holes

dark energy

The 2002 Nobel Prize in Physics was shared by scientists who opened two new windows on the Universe.

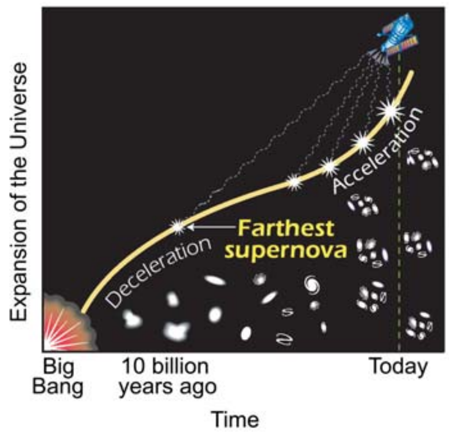
In 1962, **Riccardo Giacconi** detected for the first time a source of X-rays outside our Solar System, using a detector in the nose cone of an Aerobee rocket. Observations with his pioneering *Uhuru* satellite led to the discovery of several sources of X rays that most astronomers now believe contain black holes. Giacconi constructed the first X-ray telescopes, which have provided us with completely new images of the Universe. His contributions laid the foundations of X-ray astronomy. The company that built these early astronomical X-ray detectors also developed high resolution Computed Tomography (CT) scanning of the human body and the X-ray inspection systems used to detect illegal substances and weapons in packages, trucks, and cargo containers.

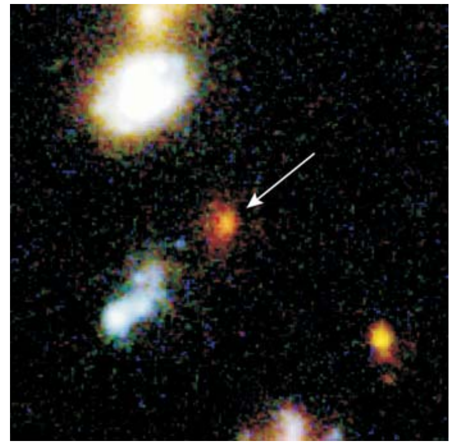


Neutrinos are particles that interact only weakly with ordinary matter, so neutrino detectors must be enormous and precise. The gigantic instruments constructed by **Raymond Davis Jr.** and **Masatoshi Koshiba** detected neutrinos from the Sun and confirmed the prediction that the Sun is powered by nuclear fusion. Koshiba's instrument also detected the neutrinos from Supernova 1987A, proving that supernovae create hot neutron stars that cool by radiating neutrinos. Davis and Koshiba created the field of neutrino astronomy. Their experiments also made the unexpected discovery that neutrinos have mass—the neutrinos in the Universe have nearly as much mass as all of the stars!

Constellation-X is the next great step in the development of X-ray astronomy blazed by Giacconi. And like the instruments of Davis and Koshiba, LISA will open for mankind a completely new window on the Universe and create the field of gravitational wave astronomy.

"The real voyage of discovery consists not in seeking new landscapes, but in having new eyes.'
—Marcel Proust





It was Edwin Hubble's discovery of the expansion of the Universe that caused Einstein to declare his introduction of the Cosmological Constant (a form of dark energy) to make the Universe static "my greatest blunder."

Ironically, it has been Hubble's namesake Space Telescope which found the farthest supernova ever seen, a dying star that exploded 10 billion years ago (right). This distant supernova offers a glimpse of the past when gravity was slowing the expansion of the Universe, then dominated by matter. In contrast, observations of nearby supernovae show that the Universe's expansion is now speeding up as the pull of a dark energy beats the gravitational attraction of matter.

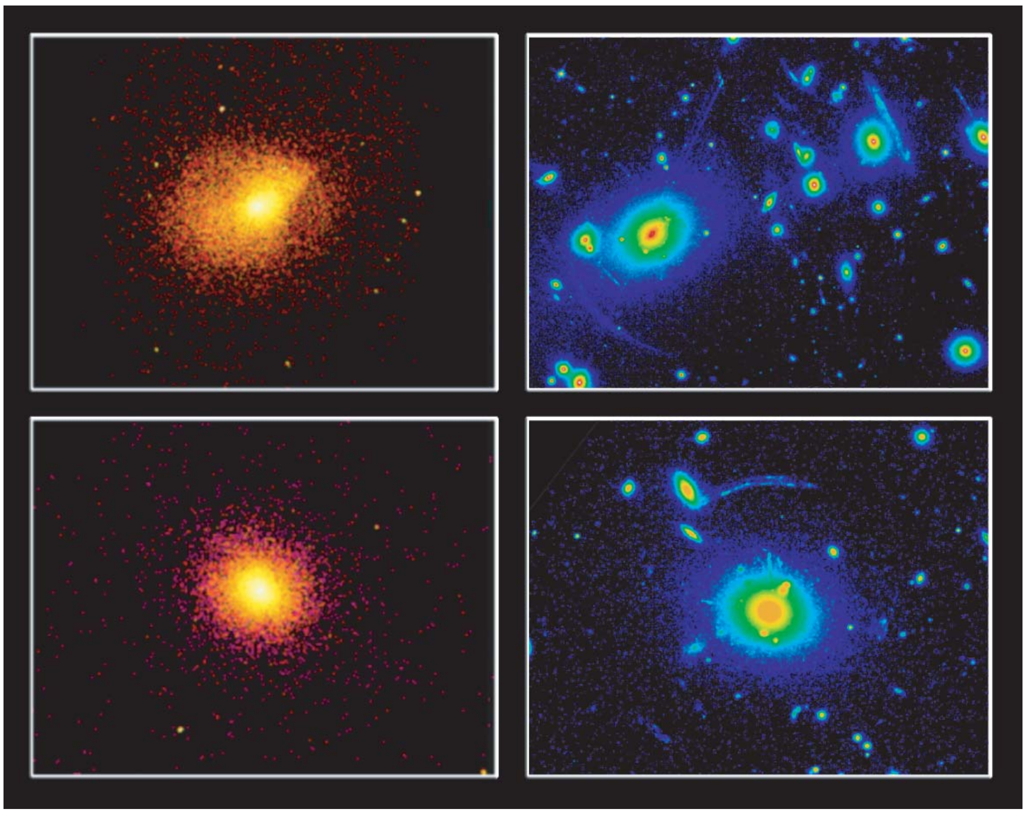
If the dark energy is indeed Einstein's cosmological constant, the long-term future of space exploration is grim: by the time the Universe is about 10 times older than it is now, only the nearest few galaxies falling into our own will still be visible: all the rest of the Universe will have become unobservably dim and red, frozen on the sky like objects falling into an inside-out black hole.

Since we have no theory of dark energy, anything we learn is an unexpected discovery. Our current understanding of how quantum mechanics and gravity are united predicts an amount of dark energy larger than observed by a factor of 10^{120}. Some modern theories predict that the amount of dark energy decreases with time, instead of staying constant as in Einstein's conception. For this very reason, dark energy is the most exciting new development in fundamental physics. Because dark energy seems to control the expansion of the Universe, we cannot predict the fate of the Universe without understanding the physical nature of dark energy. As we develop this understanding, we will be poised to answer the profound question: will the Universe last forever?

As we look at our Universe today, we estimate that it consists of five percent ordinary matter (stars, planets, gas, and dust), twenty-five percent "non-baryonic" dark matter (as-yet-undiscovered particles unlike ordinary "baryonic" matter), and seventy percent dark energy (which can be considered to have mass, too, because energy $E = mc^2$).

To learn how dark energy really works, we need to measure its properties in more detail. It is spread so thin that it can only be studied in space, where the enormous volume allows its effects to be noticed. The first step will be to measure its density and pressure and how they change with time. The Dark Energy Probe will deploy the best available technology to study this effect. Constellation-X, LISA, and the Inflation Probe will provide independent constraints to verify and increase the measurement precision.

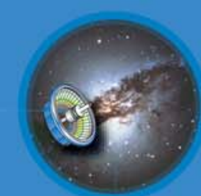
The small samples provided by the Hubble Space Telescope show that a dedicated, special-purpose instrument could provide a much better measurement of the bulk properties of the dark matter. These determine whether the energy is really constant, as Einstein conjectured, or whether it has changed over cosmic time, as suggested by some string theorists. Real data on this question would help us discover where dark energy comes from, and what the future of our Universe will be.



Observations of distant clusters of galaxies also provide independent evidence for dark energy. This montage shows two sets of Chandra X-ray Observatory images (left) and Hubble Space Telescope images (right) of two giant galaxy clusters. Most of the mass is in the form of dark matter. The X ray emission comes from the multimillion-degree gas that fills the clusters. Chandra provides detailed temperature maps for this gas to precisely determine the masses of the clusters. The gravity of the dark matter acts as a large cosmic lens on the light from distant background galaxies to produce the giant arcs seen in the images. The Hubble Space Telescope data place independent constraints on the masses of the clusters that confirm the Chandra results.

laser interferometer space antenna

constellation-x



einstein probes

Interagency Connections. Astronomical discoveries are driving the frontiers of fundamental physics and progress in fundamental physics is driving progress in understanding the Universe. *Beyond Einstein* will thus cut across the disciplines of physics and astronomy supported by DOE, NASA, and NSF. The unique capabilities of all three agencies will be essential to a coordinated attack on the science questions. This Roadmap draws on the 2000 tri-agency *Connections* science plan and implements the priorities for NASA in the 2002 report by the National Academy of Sciences Committee on the Physics of the Universe, *Connecting Quarks with the Cosmos*. Interagency partnerships will form a key component of the Einstein Probes, as they have in the GLAST mission.

Beyond Einstein: The Program

The program has three major elements that work together towards the twin visions of directly observing the birth of the Universe and directly imaging matter near the edge of a black hole. The cornerstones of the program are two Einstein Great Observatories, Constellation-X and LISA. These will provide dramatic new ways to answer questions about black holes, the Big Bang, and dark energy. The second element is a focused line of moderate-sized Einstein probes, each dedicated to the study of a specific deep question. The third element is a supporting program of forward-looking technology development, theoretical studies, and education and public outreach. Together, the three elements will enable us to grasp these questions, prove the technology to enable missions that realize the twin visions of the Beyond Einstein program, and inspire the next generation of scientists and engineers.

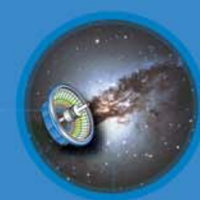
"The most incomprehensible thing about the Universe is that it is comprehensible."
—Albert Einstein

The Einstein Great Observatories

Constellation-X and LISA will use the complementary techniques of X-ray spectroscopy and gravitational waves to study black holes. They will probe space, time, and matter in the extreme environment near black holes and track their evolution with cosmic time. These two facilities will be a major resource for a broad astronomy and physics community. The National Academy of Sciences' decadal survey *Astronomy and Astrophysics in the New Millennium* developed community consensus on the most important science questions and funding priorities. It recommended both LISA and Constellation-X as high priorities for this decade.

Constellation-X will extend our capability for high resolution X-ray spectroscopy by 25 to 100 times. Its key goals are to determine the fate of gas falling into a black hole by tracking spectral features close to the event horizon, and to trace the evolution of black holes with cosmic time by obtaining detailed spectra of faint quasars at high redshift. The mission is optimized for these challenges but also provides the ability to observe other objects with unprecedented sensitivity. Constellation-X will also observe the first clusters of galaxies and be able to search for spectral features from the surfaces of neutron stars, which could finally determine the properties of matter at nuclear density.

LISA's gravitational waves offer an entirely new way to sense action in the Universe. Through them we will hear for the first time the mergers of giant black holes and the death spirals of stars they capture and swallow. Using these, we will map the knotted structure of space and time around a black hole and determine if the astonishing predictions of Einstein's theory are correct: the freezing of time and dragging of space around a black hole. LISA will also make the first complete map of merging binary stars in our Galaxy,



National Priorities. The *Beyond Einstein* science program complies extremely well with the recommendations of recent reports of the National Academy of Sciences: the decadal survey *Astronomy and Astrophysics in the New Millennium* (Astronomy and Astrophysics Survey Committee, 2001), *Connecting Quarks with the Cosmos* (Committee on the Physics of the Universe, 2002), and *Gravitational Physics: Exploring the Structure of Space and Time* (Committee on Gravitational Physics, 1999).

All *Beyond Einstein* missions have been recommended by the National Academy of Sciences. Both LISA and Constellation-X are highly ranked and strongly recommended in the two aforementioned NAS reports. Furthermore, candidate implementations of both the Dark Energy Probe (SNAP) and the Inflation Probe (CMBPol) are recommended by the Committee on Physics of the Universe. A candidate implementation of the Black Hole Finder Probe (EXIST) is recommended by the decadal survey of the Astronomy and Astrophysics Survey Committee.

future supernovae which could affect life on Earth. It will set important limits on background radiation from the early Universe and from catastrophic events, such as phase transitions in the vacuum or changes in the dimensionality of the Universe.

Both Constellation-X and LISA are critical to the goals of the *Beyond Einstein* program. One of these great observatories will begin development at the beginning of the program, and the other will begin development approximately 3 years later. NASA will determine the order based on science priority, technological readiness, and programmatic considerations.

The Einstein Probes

The Einstein Probe line is designed to address those critical science goals of the *Beyond Einstein* program which do not require facility-class observatories. The first three of these are:

- Determine the nature of the dark energy that dominates the Universe.
- Search for the imprint of gravitational waves from inflation in the polarization of the cosmic microwave background.
- Survey the Universe for black holes.

The Einstein Probes will be fully competed, scientist-led mission opportunities. Yet they will be focused on the specific scientific mysteries identified in this strategic plan. To minimize cost and maximize science return, multiple approaches to each goal will be developed and scrutinized before mission selection. An associated technology program will enable this. Some Einstein Probes may include substantial contributions from other agencies (national and international). The goal is to launch one every three years, starting about 2010.

The Einstein Probes address focused science questions identified as high priorities by the science community. The Committee on the Physics of the Universe (CPU) gave high

International Connections. International participation is a key feature of *Beyond Einstein*. The LISA mission is an equal venture between NASA and ESA, with the ESA participation fully approved. Constellation-X and the Einstein Probes have attracted international interest that will be realized when the instruments are competitively selected.

priority to determining the nature of dark energy. Polarization of the cosmic microwave background, an imprint of gravitational waves from the period of inflation, will set limits on the amplitude and frequency distribution of these waves. The study of the polarization of the cosmic microwave background was identified as an important area by the AASC report, and an Inflation Probe is a high priority recommendation in the CPU report. It is an essential prelude to embarking on a much more ambitious mission to detect the radiation directly with a Big Bang Observer. A survey of black holes by a Black Hole Finder Probe will provide a monitor for transient events that can be followed up with Constellation-X and LISA and also find targets for the Black Hole Imager. The importance of such a mission is highlighted in the AASC report.

The order in which the Einstein Probes are flown will be determined by both science priority and technological readiness. NASA will conduct mission concept studies for the Einstein Probes in order to assess mission concepts for each Einstein Probe and to evaluate their technical needs. These studies, proposed and conducted by community-based collaborations, will be fully competed and will provide the information necessary to define the technology program and later set the launch order for the Einstein Probes.

Technology and Theory

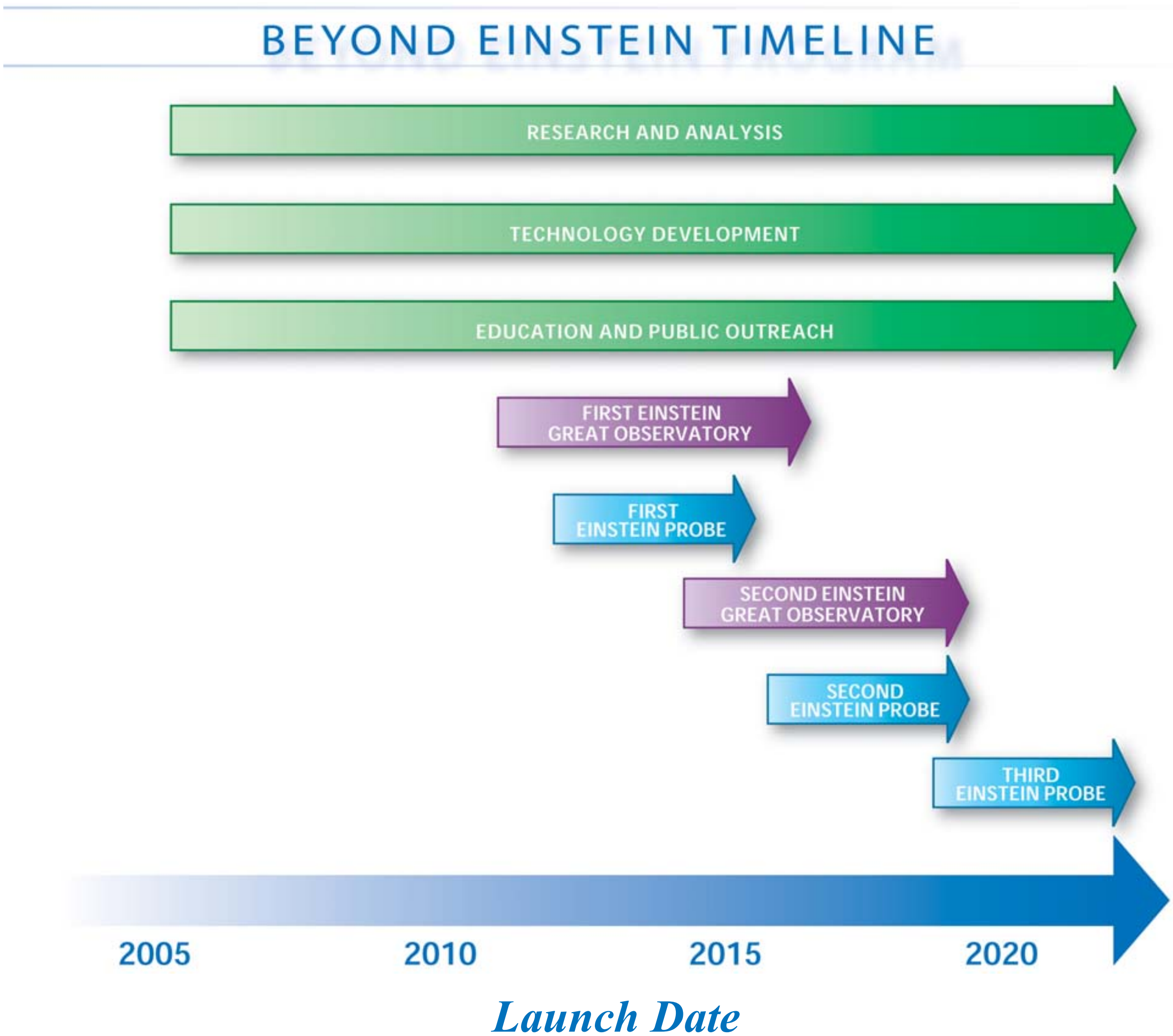
Vigorous technology development is essential for the *Beyond Einstein* program to succeed. For the Einstein Great Observatories, technology roadmaps are in place; the *Beyond Einstein* program includes the resources needed to implement them. For the Einstein Probes, key technologies must be demonstrated before the mission competitions can occur. The vision missions require a focused program to develop necessary new technologies. The National Academy of Sciences reports endorse the program leading to these vision missions: the AASC recommended investment in X-ray interferometry (for the Black Hole Imager), and the CPU report recommended development for a multi-interferometer gravitational wave mission capable of "nulling out" astrophysical foregrounds (needed for the Big Bang Observer).

"Exploring the cosmos has been something I have been drawn to for as long as I can remember. I am most interested in learning about the beginning and end of the Universe, and also exploration into black holes in terms of their role in the Universe." —from a high school sophomore responding to the GLAST Web site

The successes of COBE and WMAP owe considerable debt to theoretical studies. The programs of our roadmap are similarly complex and require an investment in theoretical modeling at all levels: from astrophysics to instrument response. Early, explicit, and stable support for theory will lay the conceptual foundations of projects, develop mission-critical analysis and modeling software, foster the growth of teams, provide training for a larger community, and help provide leadership in educational outreach. The *Beyond Einstein* program addresses these needs by including theory as part of the advanced technology needed for program success; this is consistent with the recommendation of the AASC.

Education and Public Outreach

Few scientific ventures have as much inherent power to capture the public imagination as the *Beyond Einstein* program. This power will be used to inspire the next generation of scientists, engineers, and teachers, and to support the education of our nation's students. Lesson plans and curricula based on *Beyond Einstein* will enhance science literacy. Through in-service training, the program will bring new excitement to the nation's science class-



rooms. Space scientists will bring passion to all levels of education and outreach. They will emphasize the human drama of the quest, in which people of remarkably diverse backgrounds and skills come together to design, build, and launch missions, and to develop the critical technologies that make them possible.

An Integrated Program

The three elements of the *Beyond Einstein* program are tightly linked. The vision missions will make direct measurement of signals from the true boundaries of our Universe. Constellation-X and LISA can be realized within the next decade and address pressing near-term science questions. The answers to these questions are critical to planning the scientific and technical direction of the missions which follow. The Einstein Probes address focused questions that will influence the design and observations of the more ambitious missions. The overall program is knitted together by shared theory, technology, research, and outreach.

Constellation-X will constrain the distribution of X-ray emitting matter near black holes. This is an essential step, both to prove the feasibility of imaging X-ray emission close to the event horizon and to optimize the design of the Black Hole Imager vision mission.

Competition Strategy. The acquisition strategy for *Beyond Einstein* supports the *President's Management Agenda*. The scientific goals and mission metrics are clearly defined. Maximal citizen-centered competition will be ensured by competitively selecting: (i) All NASA-provided components of the Einstein Great Observatories, LISA and Constellation-X. These include the science team, instrument providers, and spacecraft provider. (ii) The complete mission concept for the Einstein Probe missions. The proposal teams will comprise university, industry, NASA center, and government lab partners. (iii) All research, technology, and education/public outreach components of the program.

The Einstein Probes will be PI-class missions. A PI-class mission is developed by a team headed by a principal investigator (PI). The team is assembled from the university, industry, and government community by the PI. Teams propose the mission concepts and implementation strategy, including management and cost controls. NASA competitively selects one PI-led team to implement the mission under NASA's oversight. PI-class missions have been highly successful and scientifically productive in NASA's Explorer and Discovery Programs. This approach will ensure the most cost-effective, science-driven approach to the missions, promoting innovation through competition.

LISA will pioneer gravitational radiation detection in space and will make the first direct detection of waves with periods between hours and seconds. LISA and LIGO measurements together will allow us to predict the background faced by the Big Bang Observer. Combined with the results from the Inflation Probe, these will determine the frequency range and sensitivity requirements for the Big Bang Observer. Experience with LISA will determine its design.

Beyond Einstein: The Missions

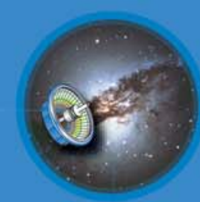
Einstein Great Observatories

Constellation X

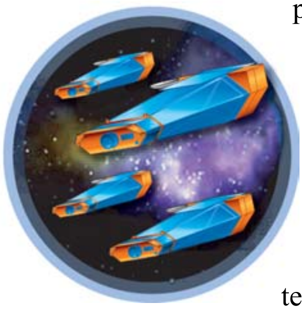
Constellation-X will measure the velocities and conditions of matter accreting onto black holes. It will deploy four spacecraft, each containing a 1.6-meter diameter telescope for measuring the spectra of cosmic sources of X rays.

Optical astronomy became quantitative astrophysics more than a half-century ago when high resolution spectroscopy became routine. It then became possible to measure the speeds, composition, and physical conditions in distant astronomical objects. The X-ray band contains spectral fingerprints for all of the abundant heavy elements (carbon through zinc) and has the potential to enable exploration of hot regions of the Universe just as optical spectroscopy has done for cooler regions. As X-ray astronomy approaches its half-century anniversary, however, imaging capabilities have far outrun spectroscopy. One-third of the sources in *Chandra X-ray Observatory* deep fields are too faint for optical or X-ray spectroscopy and their nature remains a mystery.

Constellation-X is the X-ray analog of large ground-based optical telescopes such as the Keck Observatory and the European VLT, offering spectroscopic capabilities that complement the high spatial resolution of the Chandra X-ray Observatory. Constellation-X will provide a 25–100-fold increase in sensitivity over that of current and planned missions such as Chandra, ESA's XMM, and Japan/NASA's Astro-E2. This will yield a fabu-



The **Constellation-X** design achieves high throughput and reduces mission risk by dividing the collecting area across four separate spacecraft launched two at a time. An orbit at L2 will facilitate high observing efficiency, provide an environment optimal for cryogenic cooling, and simplify the spacecraft design. Use of identical off-the-shelf spacecraft buses and a parallel production line will minimize cost.



Each satellite will contain two telescope systems: one with high energy resolution ($E/\Delta E \sim 300$–3000) for imaging X-ray spectroscopy (0.2–10 keV), and one with low energy resolution ($E/\Delta E \sim 10$) for imaging hard X-rays (to 60 keV). The spectroscopy telescopes will have 15 arcsec resolution (half power diameter) in a 2.5 arcmin field imaged by 900-pixel quantum micro-calorimeters (with 2 eV energy resolution). They will also include a set of reflection gratings (resolution 0.05 Angstrom in first order). The hard X-ray telescopes will be the first focusing optics above 10 keV and have 1 arcmin resolution (half power diameter) in an 8 arcmin field.

All of the Constellation-X technologies are an evolution of existing, flight-proven instruments and telescopes. Substantial progress has been made in key areas of technology, including lightweight X-ray mirrors, improved energy resolution and construction of larger arrays of X-ray microcalorimeters, multilayer depositions for hard X-ray telescopes, and Cadmium-Zinc-Telluride detectors for hard X-rays.

lous harvest, making spectroscopy of faint X-ray sources routine and probing conditions close to the event horizon of black holes.

The major science objectives of Constellation-X are:

- Observe relativistically broadened emission lines from Active Galactic Nuclei to determine masses and spins of their black holes, and measure the changes over time in their spectral form. The infalling atoms will provide a precise clock to measure motion in the vicinity of the event horizon. The data will challenge our understanding of the behavior of matter within the framework of the general theory of relativity.
- Investigate how matter releases energy close to the event horizon. The brightness of the inner accretion disk can be inferred, to test models for energy release in accretion disks. Phenomena more exotic than accretion, such as the interaction of a spinning black hole with surrounding magnetized gas, can extract the black hole's energy of rotation. These processes can create the relativistic jets seen in many galactic nuclei, or pour tremendous power into the inner region of the accretion disk. Constellation-X will give us the first detailed picture of these remarkable processes only hinted at by previous missions.
- Trace the evolution of supermassive black holes in quasars and active galaxies. Constellation-X will use the many black holes being found by the Chandra X-ray Observatory at high redshift to trace black hole evolution over cosmic time. The X-ray band above a few keV is relatively free of obscuration and thus allows a clear view of newly born AGN even as they are shrouded by the young, dusty galaxies in which they reside. These

observations will help determine the role of these black holes in the evolution of their host galaxies.

The Constellation-X mission has been in formulation since 1996 with a focused technology development program. Constellation-X was included as a near term priority in the 1997 OSS Strategic Plan and was reaffirmed in the 2000 OSS Strategic Plan. Recent technology investments provide a clear path for future efforts that would support launches as early as 2011.

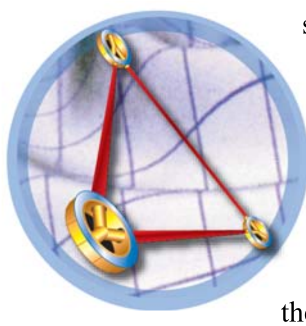
LISA

LISA will open a new window on the Universe through the study of low-frequency gravitational waves. LISA consists of three spacecraft orbiting the Sun in a triangular configuration with a baseline of five million kilometers between spacecraft.

LISA will detect low-frequency gravitational waves by measuring the changes in the relative velocity of two approximately freely-falling proof masses within each spacecraft.

"The bones of this proud woman answer the vibrations of the stars."
—Carl Sandburg, Cadenza

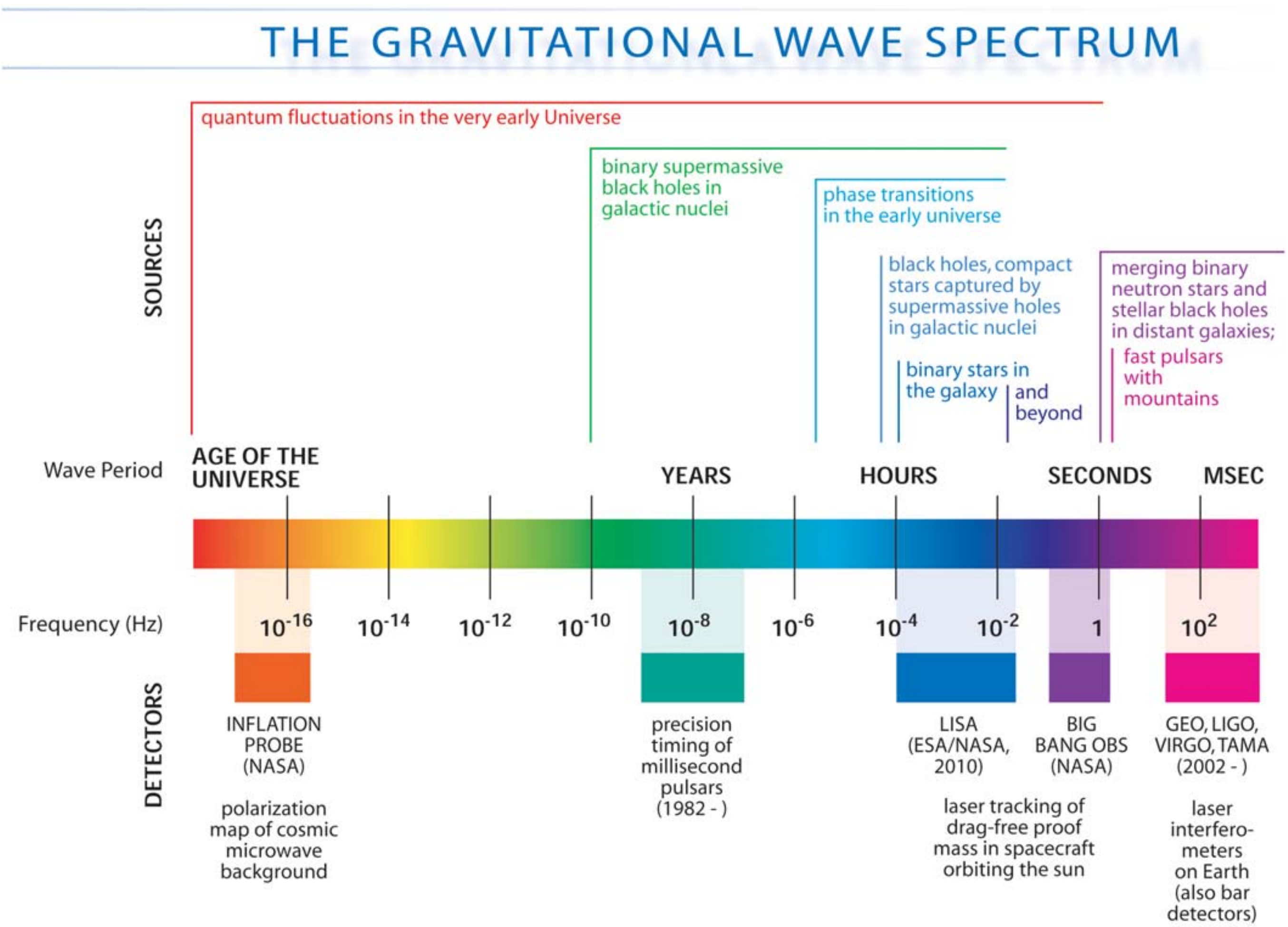
LISA consists of three spacecraft orbiting the Sun in Earth-trailing orbits, in a triangular configuration with separations of five million kilometers. At the heart of each spacecraft are two free-flying reference masses for the detection of gravitational waves. Two 30-cm telescopes direct the beams from two cavity-stabilized lasers toward the other two spacecraft. The laser light received from the two distant spacecraft is combined with the light from the local lasers. Changes in the "beat note" between the local and distant laser reveal changes in the relative velocity of the spacecraft, the signature of gravitational waves. Combining the signals from all the pairs of spacecraft will permit detection of both of the two polarizations of gravitational waves of the waves.



LISA will have greatest sensitivity to gravitational waves of periods of 100 to 1000 seconds, and will be able to detect gravitational wave bursts with spacetime strains as small as 6×10^{-21} (5σ all sky-average), corresponding to measuring 3×10^{-12} m (1σ) changes in the 5×10^{6} km separation between spacecraft over each wave period. In one year of observation, LISA will detect gravitational waves from periodic sources producing spacetime strains as small as 10^{-23} (5σ detection).

LISA will simultaneously observe a wide variety of sources from all directions in the sky. Sources will be distinguished by studying the time evolution of their waveforms. The direction of a source is revealed by the manner in which its waves' phase and amplitude are modulated by LISA's orbital motion around the Sun and its changes in orientation. LISA's ability to synthesize several interferometers with differing sensitivities to gravitational waves will enable it to discriminate isotropic backgrounds from instrumental noise.

The spacecraft use sensitive position-measuring devices to monitor the position of the proof-masses within the spacecraft ("gravitational reference units"). Micronewton thrusters will maintain drag-free control of the spacecraft about the proof masses. These two elements, viewed as the most critical to LISA's success, will be space-tested by ESA and NASA (through the ST-7 project) on the ESA SMART-2 mission, to be launched in 2006.



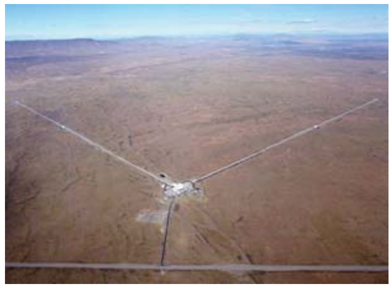
LISA will be the first instrument capable of detecting gravitational waves from already cataloged objects (several binary stars), and these will be used to calibrate LISA's performance.

Sources of gravitational waves that LISA should detect include all the thousands of compact binaries in our own Galaxy, merging supermassive black holes in distant galaxies, and the spiral descent of white dwarfs, neutron stars, and stellar-mass black holes into supermassive black holes. None of these can be detected by ground-based detectors, which are sensitive only to gravitational waves with periods in the range 0.001–0.03 seconds. In contrast, LISA measures periods between 10 seconds and a few hours. LISA may also detect violent events in the early Universe, such as phase transitions in the energy of the vacuum or in the number of dimensions, if their amplitude permits.

The major science objectives of LISA include:

- Detection of compact stars spiraling into supermassive black holes. Their orbital trajectories determine the full spacetime geometry down to the event horizon, providing the first high-precision tests of the general theory of relativity and the nature of black holes, including the famous "black holes have no hair" theorem. The desire for precise measurements of these weak signals set the sensitivity goals for LISA.

"Primordial gravity waves would be fossils from the very instant of creation. . . . No other signal survives from that era."
—M. Bartusiak in
Einstein's Unfinished Symphony



LIGO and other ground-based laser-interferometer gravitational wave observatories are beginning operation. With technological advances, in the coming decade these detectors may detect gravitational waves directly for the first time. Although they run on general principles similar to LISA, there are important differences. Because they are on the ground, the proof masses are not freely falling but are suspended on pendula; because they must use an artificial vacuum (the world's largest), the arms are 4 km long, rather than LISA's 5 million km. As a result they are optimized to detect waves of much shorter periods than LISA, and will therefore hear completely different sources. For example, LIGO will hear the final few minutes of radiation from merging black hole remnants of ordinary binary stars (about ten or more times the mass of the Sun). LISA will hear the final year's radiation from black holes (of masses ten to a million times the mass of the Sun) captured by supermassive (millions of solar masses) black holes in the centers of galaxies.

- Study of the role of massive black holes in galaxy evolution through the detection of black hole mergers. LISA will be able to observe for a year or more any merger of supermassive black holes in merging galaxies, essentially most of the visible Universe, with signal-to-noise ratio of over 1000. This will allow detailed observations of information-rich, complex gravitational wave forms from regions where spacetime is violently knotting and will put the general theory of relativity to a most severe test. LISA will also detect or strongly constrain the rate of mergers of intermediate mass or seed black holes, out to redshifts of 30.
- Search for gravitational wave emission from the early Universe. This will probe energy and length scales characteristic of the Universe 10^{-15} seconds after the Big Bang.

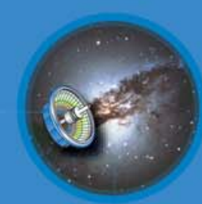
LISA has been developed and is envisaged as a joint mission of NASA and the European Space Agency. LISA was included as a near-term priority in the 2000 OSS Strategic Plan. LISA is an approved European Cornerstone Mission, with a start in 2007 and launch planned for 2010 or 2011, consistent with NASA's plans. ESA has under construction a LISA technology validation mission (SMART-2) for launch in 2006. NASA is providing its own technology validation payload for launch on the ESA spacecraft through the ST-7 project of the New Millennium program.

"Nature uses only the longest threads to weave her patterns, so each small piece of her fabric reveals the organization of the entire tapestry."
—Richard Feynman [Nobel Prize, 1965]

Einstein Probes

Dark Energy Probe

The nature of the mysterious dark energy that dominates our Universe is one of the newest and most important questions facing cosmology and fundamental physics today. Probing dark energy requires measuring precisely how the expansion rate of the Universe is, to our astonishment, increasing with time. There are several plausible strategies, including: using supernovae or other standard candles as a direct test of the distance/redshift relation; probing the evolution of cosmological perturbations through observations of large-scale



One implementation of the Dark Energy Probe involves a wide-field optical/infrared space telescope with primary aperture about 2 meters in diameter and a field of view of about 1 degree. The focal plane would consist of billion-pixel arrays of CCDs and near-infrared detectors (e.g., HgCdTe) collectively providing multicolor coverage over the range 0.4–1.7 microns. A mission of this type could search for large numbers of Type Ia supernovae in the redshift range 0.7–1.7, and provide follow-up spectroscopy and multicolor photometry for detected events. This could be accomplished by repeatedly scanning a limited region of sky about 10 square degrees. The sensitivity would be required to allow source detection down to 29th magnitude at 1 micron, and spectroscopy and precision photometry down to 25th magnitude.

Considerable technology investment would be necessary to develop reliable detector arrays of such large format. The Department of Energy has begun such development and is an interested partner in such a mission.

structure; or measuring the density of objects as a function of redshift. A mission in space is crucial to obtain high-quality data at the large redshifts ($z \sim 0.5$–2) necessary to probe cosmological evolution.

The dark energy may be Einstein's cosmological constant, now understood as an energy of the vacuum. We can use our current understanding of how quantum mechanics and gravity join to estimate what the energy density of that vacuum should be. The result is 10^{120} times larger than the experimental limits! Our understanding is clearly incomplete. An experimental measurement of a small but nonzero cosmological constant would dramatically influence the search for a quantum theory of gravity. More dramatic alternative candidates for dark energy include dynamically evolving fields or even a breakdown of the general theory of relativity.

To decide which is right, we need better measurements. The *Beyond Einstein* Dark Energy Probe will:

- Accurately determine the amount of dark energy, currently believed to comprise approximately 70% of the mass-energy of the Universe. Pinning down the precise value will both verify the existence of this mysterious component beyond any doubt and, when combined with results from WMAP and Planck, determine whether our Universe is flat (as predicted by inflation theories), spherical, or infinite and curved.
- Greatly increase our sensitivity to time variations in the dark energy density. Einstein's original cosmological constant was constant in time, as the name implies. We now know that his constant is equivalent to an energy density of the vacuum. If the Dark Energy Probe shows that the dark energy density is constant in time, it will have discovered a nonzero vacuum energy, a priceless empirical clue in the quest to reconcile quantum mechanics with the general theory of relativity. If the Dark Energy Probe shows that the dark energy density varies with time, it will have discovered a new dynamical field or a failure of Einstein's general theory of relativity—with dramatic implications for the future of our Universe.

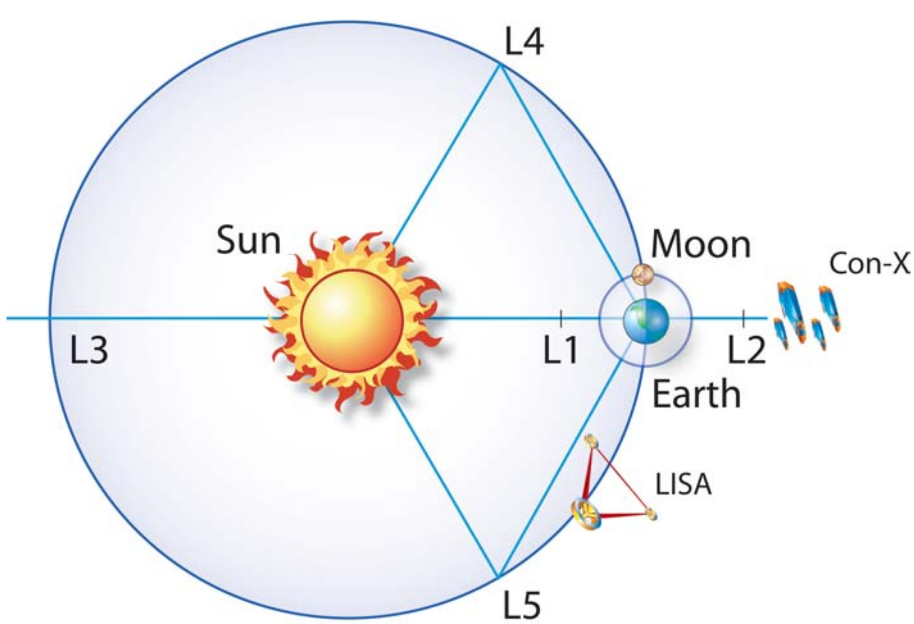
Inflation Probe

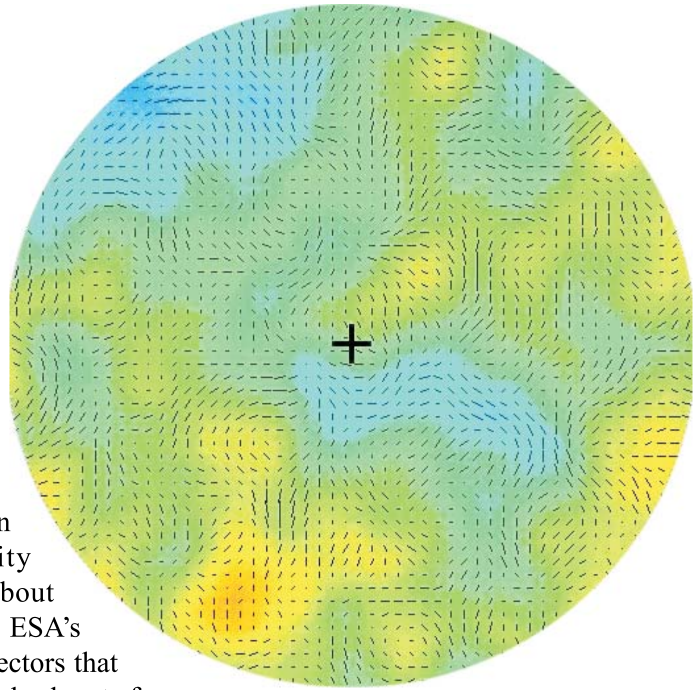
The *Beyond Einstein* Inflation Probe will seek the imprint of gravitational waves on the relic Cosmic Microwave Background (CMB). These quantum waves should reveal if and how a mysterious "inflation" field stretched and smoothed our Universe. One promising approach would use a 2-meter cooled telescope located at L2, equipped with large arrays of polarization-sensitive detectors operating between 50 and 500 GHz.

Just before the Universe became neutral, electrons scattered the cosmic microwaves. This generated a pattern of polarization related to the temperature fluctuations of the CMB. Both density fluctuations and gravitons (gravitational wave quanta) produced in the very early Universe combined to determine this pattern. Temperature anisotropy studies, such as those made by COBE and WMAP, cannot distinguish the density and graviton components. Fortunately, these two sources of fluctuations generate different patterns of polarization, allowing them to be separated. However, the graviton component is likely to be at least 100 times fainter than the density component, first detected in 2002 and to be mapped to high sensitivity by ESA's Planck mission (to be launched in 2007). The Inflation Probe will:

- Map the polarization of the CMB and determine all the sources of this polarization on both large and small scales. This will provide the most precise test yet of the gravitational theory for the origin of galaxies and structure in our Universe.

Many of the *Beyond Einstein* missions require that they be located far from Earth. The Earth-Sun L2 point is located approximately 1.5 million kilometers in the anti-Sunward direction along the line joining the Sun and the center of mass (barycenter) of the Earth-Moon system. Constellation-X and the Inflation Probe require thermal control and will orbit around L2, as does the current WMAP mission. LISA's stable five million kilometer baselines require that its spacecraft orbit the Sun in orbits trailing the Earth's.





This simulation of the cosmic microwave background shows the circular patterns left in its polarization by gravitational waves as long as the Universe.

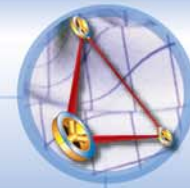
To detect the effect of gravitational waves from inflation on the polarization of the CMB will require all-sky polarization maps with sensitivity about 1 μK per pixel, about 20–100 times better than ESA's Planck mission. The detectors that will fly on Planck are already close to fundamental quantum limits, so improvements in mapping sensitivity must come from large increases in the number of detectors and cooling the optics to reach the background limit of the CMB itself. The angular resolution of the maps must be a few arcminutes to allow the true gravitational wave signal to be distinguished from secondary sources of polarized CMB signals, such as gravitational lensing of the density component to CMB polarization. Consequently, the Inflation Probe will require at least a 2-meter class telescope, probably cooled, and equipped with focal plane arrays containing thousands of pixels. Each pixel must also be observed simultaneously from 50–500 GHz to allow astrophysical foregrounds to be subtracted. The signals from inflation are likely to be mixed with confusing foregrounds and effects from gravitational lensing, so preparatory theoretical and observational work are essential to the success of this effort.

- Search the CMB for the signature of gravitational waves from the Big Bang. This will test theories of the very early Universe, such as inflation models. It will also test physics at energies that are currently inaccessible by any other means.

Black Hole Finder Probe

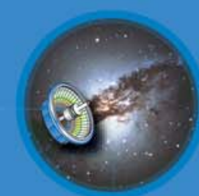
The supermassive black holes at the center of our own Milky Way and its companion, the Andromeda galaxy, are normally quiet, perhaps flaring brightly every 10 thousand years when they swallow a star from their surroundings. Even the three closest supermassive black holes now swallowing gas are hidden in galaxies that otherwise appear normal. Yet these black holes have had a dramatic effect on the formation and evolution of galaxies—and even life. The optical appearance of a galaxy usually does not advertise the presence of a black hole, or tell us what it is doing.

Did massive black holes form when galaxies formed? Did they slowly grow later? How fast are they still growing? We need a census of accreting black holes to find out.



laser interferometer space antenna

constellation-x

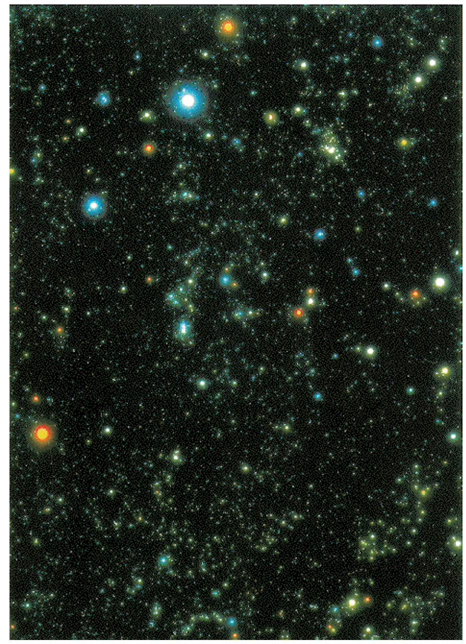


einstein probes

The Black Hole Finder Probe could be a hard X-ray survey mission, consisting of a very large-area (about 4–8 square meters) array of imaging solid-state detectors (Cadmium-Zinc-Telluride) which view the sky through wide-field coded aperture masks. The required angular resolution is about 3–5 arcmin.

To penetrate gas and dust, an X-ray Black Hole Finder Probe should be sensitive in the 10–600 keV band. To perform a reliable census, the 5σ flux sensitivity in a 1 year survey at 20-100 keV should be $F_{lim} \sim 5 \times 10^{-13}$ erg cm^{-2} s^{-1}, comparable to the flux limit of the all-sky soft (0.5–2.5 keV) X-ray survey conducted by ROSAT.

The centers of bright sources will be located to about 10 arcsec so that counterparts at optical/IR/radio wavelengths can be identified. The faintest survey sources would have 1 arcmin centroids, sufficient for identification with bright galaxies or as a finder for higher resolution instruments like Constellation-X.



The constellation of Orion as seen in soft X-rays by ROSAT. Besides the familiar stars, the X-ray image reveals white dwarfs, supernova remnants, and accreting black holes at the edge of the Universe.

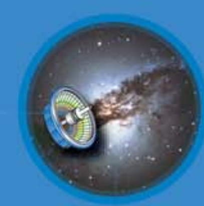
The *Beyond Einstein* Black Hole Finder Probe will do this. It will perform the first all-sky imaging census of accreting black holes: from supermassive black holes in the nuclei of galaxies, to intermediate mass (about 100–1000 solar mass) holes produced by the very first stars, to stellar mass holes in our Galaxy.

A veil of dust and gas currently hides most accreting black holes from our view. High-energy X-rays, infrared, and radio waves can penetrate this veil. Of these, X-rays can best be distinguished from emission from stars, so one promising approach is a wide-field telescope operating in the hard X-ray band. The Black Hole Finder Probe will enable a range of studies of black holes and the extremes of astrophysics:

- Black Hole Finder Probe will survey the local Universe over a wide range of black hole obscuration and accretion rates. It can identify the most luminous obscured black holes at larger redshifts to estimate the growth rate of massive black holes. Follow-up studies with Constellation-X and eventually the Black Hole Imager will measure fundamental black hole properties (spin, mass) in the best targets.
- Black Hole Finder Probe will discover ordinary stars being torn apart as they approach black holes. It will complement LISA, which will see the gravitational waves from the initial phases of these events involving small stars, and also the capture of neutron stars and black holes too small to be torn apart.

laser interferometer space antenna

constellation-x



einstein probes

Einstein Vision Missions

A Big Bang Observer

Of all waves and particles known to physics, gravitational waves interact the least. Thus they carry information to us undisturbed from the earliest moments of the Universe, when it was so dense that neither light nor neutrinos could escape. The radio waves of the cosmic microwave background escaped and began their journey to us when the Universe was 300,000 years old. The hydrogen and helium around us formed when the Universe was a few minutes old. Gravitational waves escaped on a journey to us when the Universe was less than 10^{-35} seconds old. The ultimate goal of the Big Bang Observer is the direct detection of these gravitational waves.

Like electromagnetic waves, gravitational waves cover a broad spectrum. Understanding the expansion history of the Universe at the moments when quantum foam was becoming our familiar space and time requires measuring the gravitational wave relics from this era at least two widely spaced frequencies. The Inflation Probe will search for the effects of waves with periods of billions of years; the Big Bang Observer will seek a direct detection of waves with periods of 0.1–10 seconds.

At longer periods, the confusing foreground from astrophysical sources is hopelessly large. At the shorter periods at which ground-based gravitational wave detectors must operate, the expected signal from inflation becomes too weak to detect. In between, at periods of 0.1–10 second, lies a window of opportunity. In this frequency range, the primary source of foreground signals is neutron star binaries several months before coalescence, and these are few enough that they can be identified and removed. Yet the signal from the quantum foam of the early Universe is still within reach.

To reduce the risks, it may be desirable to begin with a less sensitive pathfinder mission to make the first exploration of the Universe in this gravitational wave frequency window, whose astrophysical sources are expected to include the seeds of black hole formation, the first stars, and galaxy formation.

- The Big Bang Observer has the goal of direct detection of quanta of the gravitational field created during inflation. This could give us a direct view of the creation of space and time and, in combination with results from the Inflation Probe, determine the nature of the vacuum at energies far higher than we can hope to reach with ground-based accelerators.
- The Big Bang Observer will reach this goal by identifying (and subtracting) the gravitational wave signals from every merging neutron star and stellar-mass black hole in the Universe.
- Measurement of these merger signals will directly determine the rate of expansion of the Universe as a function of time, extending the results of the Dark Energy Probe.
- The Big Bang Observer can also pinpoint gravitational waves from the formation or merger of intermediate mass black holes. These are believed to form from the first massive stars born in our Universe. They will also enable even finer measurements of the structure of spacetime around black holes than will be possible with LISA.

"Of all the conceptions of the human mind, from unicorns to gargoyles to the hydrogen bomb, the most fantastic, perhaps, is the black hole."
—-Kip Thorne in Black Holes and Time Warps: Einstein's Outrageous Legacy

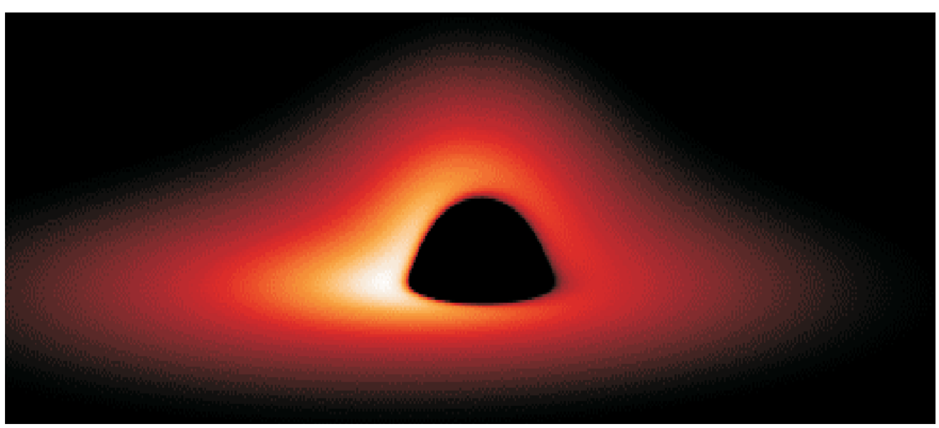
A Black Hole Imager

The goal of the Black Hole Imager mission will be to image directly matter falling into a black hole, with resolution comparable to the scale of the event horizon. An angular resolution of 0.1 micro-arcsecond (a million times better than the Hubble Space Telescope) is required to do this for accreting black holes at the centers of nearby galaxies. This resolution can be achieved at high radio frequencies and at X-ray wavelengths.

A simple image, while exciting in concept, is not sufficient to study the dynamics of the inner regions. To better disentangle the complicated dynamics near the black hole will require spectroscopy to map the speed as well as position of gas as it nears the event horizon. This will require spectroscopically resolved imaging at the wavelengths of X-ray lines.

The science objectives for a black hole imaging mission are:

- Map the motions of gas in the vicinity of a black hole event horizon and compare them to predictions based on the general theory of relativity. In bright accreting black holes, the essential physical conditions can be measured via imaging spectroscopy of fluorescent features from the accretion disk's surface, allowing a quantitative test of strong field general relativity. Constellation-X takes a first step by demonstrating time-resolved spectroscopy of relativistically broadened X-ray lines but without the imaging capability of Black Hole Imager.
- Map the release of energy in black hole accretion disks. The underlying mechanisms by which gas swirling into black holes loses energy are not well understood. A direct image of the inner disk could reveal the details of this process.
- Determine how relativistic jets are produced as well as the role of black hole spin in this process. The ultimate irony of black hole accretion is that rather than swallowing everything, somehow many black holes manage to generate relativistic jets, by mechanisms that remain a mystery. Imaging and spectroscopy will also provide direct tests of models that predict that magnetic fields extract energy from the black hole itself to power these jets.



A simulated Black Hole Imager view of an accretion disk around a black hole. The bending of light rays by the black hole makes the back side of the disk appear raised.